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THE NONDESTRUCTIVE INSPECTION OF AIRCRAFT TIRES BY USE OF PULSE-ECHO ULTRASONICS

PHASE REPORT

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SUMMARY

INTRODUCTION

It is currently mandated that rebuilt aircraft tires for NAVAIRSYSCOM (Naval Air Systems Command) be one hundred percent inspected by the rebuilding contractor. Under AirTasks A3405344/200B/2F00461406 and A4020AEB03/WUA41111H/01 the NAVAIRDEVCEN (Naval Air Development Center) is developing a prototype system for inspection of aircraft tires. Due to recent technological advances in ultrasonic flaw detection apparatus (broad band characteristic), it is shown that ultrasonic, pulse-echo inspection of aircraft tires is now feasible.

SUMMARY OF RESULTS

Fundamental properties of rubber and rubber composites pertaining to ultrasonic inspection of aircraft tires have been briefly investigated as indicated in table I. A manually operated tire inspection system with photographic data recording has been fabricated utilizing the pulse-echo ultrasonic technique. Data recording equipment has been selected to furnish permanent, real time, flaw records necessary for a semi-automated inspection system. This system has demonstrated the ability to meet current requirements of detecting at least ½ inch separations throughout the tread down to the carcass bondline in tires containing tread fabric reinforcement.

Tire defect standards are being manufactured, both in-house and by new and rebuilt tire manufacturing companies, for further inspection system evaluation.

CONCLUSIONS

From the results presented in this report, it is established that the pulse-echo, ultrasonic technique is feasible for aircraft tire inspection. Pulse-echo ultrasonics holds several significant advantages over other inspection techniques, such as flaw depth perception, application to flight line maintenance inspection, low system cost, and acceptable inspection time.

The manual prototype system has demonstrated the capability for detection of internal separations and repair areas at least as small as the maximum size presently allowed during the rebuilding of high speed, high performance aircraft tires. Inspection capability in the area of deep carcass separations and cord fractures can not be properly evaluated until new tire defect standards are available.

New methods of processing ultrasonic signal information proposed by NAVAIRDEVCEN, as far as they have been substantiated in this report, exhibit the possibility of enhancement and simplification of this inspection technique.

RECOMMENDATIONS

Due to the success of the current effort, and the favorable consensus expressed during reference (a), recommendation is made for continuance of the current development program including the assembly of a complete, automated, working model, tire inspection system. Efforts should also be continued to extend the inspection range to include the tire side wall and bead areas.

Further development of the ultrasonic, pulse-echo technique should be directed toward the area of maintenance inspection with the construction of a suitable working model for in situ inspection of aircraft tires on the flight line. As part of this maintenance application, consideration should be given to the utilization of the same ultrasonic system for maintenance inspection of wheels in addition to tires.

It is further recommended that nondestructive test and inspection techniques be introduced into current dynamic, dynamometer, tire testing programs to improve reliability and save time in the evaluation of aircraft tires. Nondestructive test techniques applied during dynamic testing may allow early determination of tire acceptability, thereby reducing testing costs and time. A considerable effort is yet required to determine the effect of internal flaws with respect to tire failure. Correlation of nondestructive inspection results, from ultrasonic testing for example, with failure data (dynamometer test) will yield information on the size, depth, location, and propagation rates of critical flaws.

Extension of the present brief fundamental study of ultrasound propagation in aircraft tires is highly desirable. Exact limitations of the present ultrasonic pulse-echo inspection system should be determined, and the newly proposed techniques should be fully evaluated. The addition of data processing in the form of analogue and digital analysis should be considered to increase inspection capability. Such advanced processing could lead to a satisfactory automatic decision function for the presence of defects and a go-no-go capability, which is necessary for fully automated inspection.

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BACKGROUND

New tires currently comprise one of the more costly logistic support items for Naval aircraft. However, suitable used tires can be retreaded at one fourth the average cost of the original new tire, reference (b). Consequently, ninety different types of tires are being retreaded by several qualified tire rebuilding companies, reference (c). Since each of these companies has more than one plant location, reference (c), there results a considerable range of rebuilding quality among and between the various facilities. Therefore, the inclusion of one or more nondestructive inspections during the rebuilding operations would provide for uniform quality while also providing a means of gauging the ability of a rebuilt tire to withstand additional life cycles, reference (d).

The addition of nondestructive inspection techniques to new tire procurement, to maintenance inspection, and to the current dynamic qualification and destructive test programs will yield considerable additional safety and savings. Automated nondestructive tire inspection systems must be developed which will enable acceptance inspection of each new and rebuilt tire and inspection during routine in-service maintenance, if maximum reliability and efficiency is to be achieved.

There are several methods with proven applicability to nondestructive tire inspection, reference (e). Ultrasonic methods of inspection are outstanding from the viewpoints of inspection cost, inspection time, and fault resolution. The pulse-echo, ultrasonic technique offers even more advantages due to its characteristic high sensitivity to internal composition and flaw depth perception. These characteristics allow the location of internal inhomogeneities in all three space dimensions, thus enabling complete mapping of the placement of structural elements comprising the tire. Further, since the pulse-echo technique requires access only to the tire exterior, it also has the potential of flight line tire inspection. This is a critical application which no other established method has proven able to accomplish.*

In the past, the pulse-echo, ultrasonic technique has been studied as a possible nondestructive tire inspection method with little success, references (f), (g), and (n). It is now obvious that such conclusions were based upon improper system parameters and limitations in ultrasonic technology. Recent improvements in the technology have significantly improved the attractiveness of the pulse-echo ultrasonic technique for tire inspection, references (e), (i), (j), (k), (l), and (m). An up to date survey of government projects, reference (n), has shown that no Department of Defense effort has been expended on tire inspection. Thus, the present program is significant since it is the only Department of Defense effort directed to the nondestructive inspection of tires.

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* While the methods or radiographic, infrared, and holographic inspection may be accomplished with access to the tire exterior alone, these methods have not shown practicality in the maintenance application despite a considerable development effort.

Related to the problem of providing an inspection system is the determination of the relation between actual tire failure phenomena and internal flaws. Little effort has been expended on this most important task to date. However, active testing programs have been initiated, reference (O).

Concurrent with the study of flaw detection and evaluation based upon failure data, is the necessity for known flaw standards in both new and rebuilt tires. The present effort includes procurement of aircraft tire defect samples necessary to quantitatively evaluate an inspection system capability. In turn, nondestructive test procedures have been of value in development of the optimum processes utilized for the fabrication of these defect standards.

FUNDAMENTAL PROPERTIES OF AIRCRAFT TIRES

Ultrasonic, pulse-echo methods hold such rewards for tire inspection that it is important to review the technique in light of recent advances in the state-of-the-art of ultrasonic technology. The first step toward development of a tire inspection system based upon ultrasonics was a study of the materials and specific structures of aircraft tires in relation to the propagation of ultrasound.

Several methods of tire construction exist which result in tires of widely differing acoustic characteristics. Figure 1 shows a typical tire cross section. Variations are due to the presence or absence of the tread reinforcement, number, density, and material of the carcass plies, liner material, exact rubber compounding mixtures, and the overall physical dimensions for different sizes and styles of aircraft tires.

As an ultrasonic wave progresses at the speed of sound into the tire, energy is reflected by inhomogeneities, reference (f). This principle is the foundation of the pulse-echo, ultrasonic inspection and allows an examination of internal features through detection and analysis of reflected acoustic energy. It is well known that the pulse-echo method has a greatly enhanced sensitivity to changes in internal properties as compared to the through-transmission ultrasonic technique (which examines the ultrasonic energy able to completely penetrate the test object) when the reflected energy is a small percentage of the overall acoustic energy.

The previously mentioned variations in tire construction cause the results of ultrasonic inspection to vary with tire style. There are certain common properties however, and among these are the acoustic properties of rubber itself. From Table I, it may be seen that the most significant obstacle to ultrasonic inspection is associated with the large attenuation exhibited by rubber. While a reduction in the frequency of the sound does allow more acoustic energy to penetrate rubber and rubber composites, the corresponding increase in wavelength, or physical extent of the disturbance, results in a loss of spatial

resolution. For example, at $1 MH_z$ in rubber, the wavelength is approximately 1.5 mm, while at 100 KH_z, it becomes 15 mm. Since typical carcass cord spacing is on the order of a millimeter, the longer wavelength does not permit resolution of individual carcass layers, reference (e). The fact that the carcass and reinforcement cords have very low densities and do not support ultrasonic waves makes these elements excellent reflectors. Pulse-echo, ultrasonics can therefore easily detect and probe these tire elements.

Water and rubber have nearly the same ultrasonic velocity and density and hence very close acoustic impedances. Coupling ultrasonic energy from a water-to-rubber medium is, therefore, relatively efficient. For example, for an ideal, or plane and smooth, water-rubber interface the coefficient of reflection for plane waves is approximately 1.8×10^{-3}, which means that 99.9% of the energy will enter the rubber from the water. Water coupling to the tread surface should be ideal for automated tire inspection. Addition of glycols or other select chemical agents, which are harmless to rubber, to the water couplant will improve the acoustic match and further reduce the reflected energy arising from this interface. Minimized reflected energy from this source is necessary in order to inspect tires in the region where tread design could otherwise produce extraneous results. Also, reduction of this echo in combination with sufficient water path will help eliminate spurious signals interfering with detection of small echoes. Direct contact inspection is possible, although more difficult due to surface irregularities, variable transducer-surface reaction, nearfield loading of the transducer, and transducer noise.

In order to obtain satisfactory spatial resolution it is necessary to generate short pulses of ultrasound. The spatial extent of the ultrasonic disturbance is approximately cn/f_o, where c is the sound velocity f_o the predominant frequency, and n the number of cycles excited. Frequency content of short radio-frequency bursts of ultrasonic energy is illustrated by figure 2, reference (p). Typical pulses with a center frequency of $f_o = 1 MHz$ and pulse length of $T_o = 1.5 \times 10^{-6}$ seconds, introduced into natural vulcanized rubber, allows a resolution of only those defects more than 2mm apart in the direction of propagation. This assumes that further resolution degradation, due to dispersion, for example, is negligible. The generation of such pulses requires a broad-band ultrasonic transducer. Advances in the state-of-the-art of transducer fabrication and materials have made possible broad-band transmitting and receiving elements with excellent conversion efficiencies. Further advantages in the use of broad band ultrasonic tranducers, with regard to desirable radiation field patterns, have been discussed in current literature, reference (q).

Connected with the large frequency dependent attenuation of rubber is the fact that non-sinusoidal signals suffer changes in wave shape or dispersion during propagation. In effect, the material functions as a low pass filter to the broad-band ultrasonic pulse. Dispersion

increases with the length of the propagation path in such materials. The result is an apparent progressive reduction in the predominant frequency of the ultrasonic wave packet and physical spreading of the wave packet in space. As a consequence, spatial resolution is significantly reduced with increased depth into the tire. However, as defects deep within the carcass are presently considered less significant than similar defects closer to the tread, references (a) and (o), this limitation should not prove serious. Figure 3 demonstrates typical progressive dispersion of an ultrasonic pulse in rubber.

To overcome the loss of energy and dispersion during propagation, a broad band, high gain detector is required. In the pulse-echo technique, the same transducer functions as both ultrasonic generator and sensor. The previously required broad band nature of this element as the transmitter also allows efficient operation as the receiver in the detection of the reflected dispersed waves. A broad band, low noise, high efficiency transducer is therefore critical to succesful tire inspection.

Use of broad band, high gain electronic amplification will allow detection, display, and processing of the reflected signals. Limitations of this approach are due only to the finite signal-to-noise ratio of the received information, assuming electronic noise is negligible. Increased signal levels over the electronic noise may be realized through increased transmitted ultrasonic energy and focused transducers. The use of broad band ultrasonic systems for penetration and resolution in materials exhibiting large attenuation and dispersion have been confirmed by others, reference (r).

Figure 3 shows typical signal levels generated in an ultrasonic transducer. The ultrasonic wave depicted in those photographs was launched by the application of a 200 volt pulse to the transmitting/receiving transducer. The wave, subsequently traveled one-half the specified propagation distance in vulcanized, filled, natural rubber, suffered a total reflection from a plane-air interface, and returned through the remaining half path length distance to the transducer. These acoustic signals produce electric voltages on the order of tens of millivolts. Since attenuation for a round trip path in a typical tire* is approximately 100 db more than the loss involved in the path of figure 3, signals on the order of a microvolt are to be expected from reflections at the tire liner-air interface. Detection of such feeble, distant echoes is most difficult. However, detection of echoes from flaws, not quite so distant from the tread, is certainly possible. In fact, while a clear distinct echo from the rear tire surface in the tire described is not observable on standard inspection equipment**, there is positive indication that the rear surface may be monitored.

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* Data is for a 17.00-20, type III, cut resistant, 22 ply rated (18 actual plys) tire with metal reinforced tread.

** Lehfeldt MPT-10 pulser-receiver, Panametrics VIP-I-IT transducer

This positive indication was noted while changing the acoustic impedance of material in contact with the liner, whereby a definite but slight change in the received echo pattern was observable at the expected A-scan location. Such penetration ability has not previously been reported in the literature.

NEW TECHNIQUES FOR ULTRASONIC INSPECTION

There are additional phenomena which can add to the attractiveness of the ultrasonic, pulse-echo method of tire inspection. Since the carcass resembles a regular, stratified medium, an interference effect will occur at the proper frequency. In the steady state this phenomena has been used to advantage in commercially available equipment, but it has not been exploited in pulsed systems nor for tire inspection. With the short spatial extent of pulsed waves, this phenomena will allow examination of a few adjacent plies simultaneously. A ply defect will tend to destroy the fundamental nature of the interference and hence become observable. For a ply spacing of "d" millimeters, a frequency of C/2d is required to observe this interference where C is the ultrasonic wave velocity in mm/sec. Since typical ply spacing is on the order of d·1mm, a center frequency of f_0=750 KHz is required. Broad band signals are desirable for the exploitation of this effect because they insure the presence of acoustic energy at the necessary frequency even when ply spacing is varying within a particular tire and from tire to tire. In competition with the interference effect is the large attenuation.

For very low coefficients of reflection R, or when the reflected energy is a small fraction of the total incident energy as is the case for small composition changes in rubber, the amplitude of the reflected wave is highly sensitive to local changes in material properties, as exhibited in figure 4. The reflected wave is also highly dependent upon the specific geometry of the interface. As present experimental results have suggested, it may be feasible to monitor one of the more predominant internal interfaces, such as the reinforcement layer or retread bond-line, to assess the integrity of the tire areas interior to these interfaces based upon these effects. A correlation of the variation in reflected energy originating from these easily distinguished interfaces, with previous defect observations, may allow significant simplification of the inspection evaluation as illustrated in figure 5. This technique has not been previously suggested or applied to flaw detection in tires by others in the field.

A phenomena which has been previously studied but not generally applied to the enhancement of flaw detection is the use of multiple echo detection. It is easy to show that the reflected energy varies as R^{2n} for the nth internal reflection, where R is the wave amplitude reflection coefficient. Usually the first internal reflection, where n-1, is monitored so that the reflected amplitude signal varies in direct proportion to R. Slight variations in the specific acoustic impedance and the material properties of the interface causing reflection will therefore be correspondingly magnified. Two effects

hamper the use of multiple-echo analysis, but these do not eliminate its effectiveness. First, attenuation arising from the additional propagation path length and additional reflections acts to reduce the signal levels of multiple echoes. Secondly, complication of the pulse-echo display results from multipath phenomena as described by Mundry, reference (s).

For example, in a typical rubber composite and at an internal interface which is characterized by a reflection coefficient of $R=10^{-2}$ or 1% reflected energy, a change in interfacial properties might result in a reflected signal variation of 2.5 db. Examination of the second echo will produce a corresponding variation of 5 db, and the third echo variation would be 7.5 db. Signal loss from the additional reflections is about 40 db per echo plus an additive factor of 17.4 ADn where A is the material attenuation number, D is the interface depth in the material, and n is the number of the reflection. For a tire bond line* the second and third echoes would be approximately 50 db and 100 db respectively below the primary echo level. Such predictions have been qualitatively confirmed experimentally.

INSPECTION SYSTEM DESCRIPTION

The previous brief review of interaction properties for ultrasonic waves and rubber composites determines certain requirements for an ultrasonic, pulse-echo tire inspection system. Necessary criteria are low noise, high efficiency, broad band transducers; low noise, high gain, broad band electronic processing, and water coupling. For semi-automated inspection it is desirable to have electronically gated monitors and a defect recording and mapping system. Gating systems are standard accessories, and both C-scan and compound A-scan displays may be useful for defect analysis.

Under the present development program, reference (t), standard equipment is to be integrated into a tire inspection system. The inspection system is schematically diagrammed in figure 6. After considerable evaluation of modern, ultrasonic transducers, it was concluded that the broad band series of sensors made by Panametrics, the VIP-I-II, best fulfilled these requirements. A center operating frequency of approximately 1 MH_z was selected. Several ultrasonic pulser-receivers would probably have sufficed, however, delays in availability of instruments for evaluation narrowed selection to the Lehfeldt MPT-10/MESWAIRT/SWAIRT with two flaw gates and an analogue echo amplitude output for recording. This instrument has an additional feature of special data enhancing circuits including noise suppression. Photographic A-scan and echo amplitude recording is presently in operation with this instrument. An automatic C-scan system utilizing a facsimile drum recorder is under construction.

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* In a 17.00-20, Type III, cut resistant, 22 ply rated (18 plys actual) tire with metal reinforced tread.

A mechanical sub-system for holding and rotating the tire consists of a standard tire handling machine, Branick GA/ER/EF/S. This was modified to allow a slower and adjustable scan speed of the tire under test. The current rate is approximately 2 RPM minimum. Positioning of the transducer search unit is accomplished manually with a modified microwave slotted line carriage, search tube, and miniature angle manipulator. The water immersion tank is a standard tire trough with the addition of a plexiglass window to allow observation of the transducer alignment.

Before the problem of tire fault detection may be properly investigated, tires with known standard defects must be procured. Since no standard procedures for the manufacture of known tire defects have been established, this area requires considerable effort. Presently, two rebuilt tires with built in defects have been made available.* These tires have been examined by various inspection techniques including x-ray, infrared, holographic, and through-transmission, ultrasonic methods, in round robin tests to produce some knowledge of the true nature of the built-in defects. Soon to be completed are new tire defect standards. With such standards, the ability to detect and inspect for carcass separations and flaws will be more precise and quantitative in nature.

Inspection Results

Defects as small as ½ inch diameter separations** at the tread-bond line in fabric tread reinforced tires are easily distinguished. Defects deeper in the carcass structure have been noted in laboratory tests, however, definite confirmation with the immersion system requires a standard defect tire of new construction.***

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* These tires which have been used at NAVAIRDEVCEN for evaluation of the present inspection systems are:

1. 26X6.6, 16 ply rating, SN 131451630E, retread defect tire standard made by Flight Treads of Atlanta, Atlanta, Georgia.

2. 26X6.6, 16 ply rating, SN 92750501, retread defect tire standard made by Air Treads of Atlanta, Atlanta, Georgia for the U.S. Air Force, Hill AFB.

** This is the minimum size defect required to be detected for approval of tire inspection systems necessary for tire rebuilder qualification under reference 4.

*** Rebuilt tires with so called defects below the tread bond line contain in reality only bond line defects. The reason is that all deep defects require back filling to the rebuild bond line and hence produce inhomogeneities first appearing at bond line.

The new method developed at the NAVAIRDEVCEN of observing variations in near interfaces to investigate more interior structural defects, has been substantiated by experimental results. In tread reinforced construction the echo received from the reinforcement layer appears to be higly sensitive to internal properties of the tire. Figure 5 illustrates the magnitude of this effect and its ability to determine tire integrity.

While other inspection techniques have been successful in detecting the defects shown in figures 7 and 8 through round-robin tests, the pulse-echo method is the only one which indicates the depth of such defects in the tire and depth placement of internal elements. Depth information is extremely important because the severity of a flaw with respect to tire integrity is highly dependent upon its depth, reference (o). Also, other successful methods employed in these round-robin tests are not applicable to maintenance inspection in situ.

TABLE I
ACOUSTIC PROPERTIES OF RUBBER AND RUBBER COMPOSITES

Material	Attenuation @ 1 MH$_3$	Velocity 10^5 cm/sec
Cured, carbon, filled natural rubber	3.85 db/cm	1.53
Pre-cured tread stock (Bandag, Inc. product)	8.35 db/cm	1.4.
Cured, carbon, filled natural rubber with gross proposity	12.0 db/cm	---
Two ply automotive tire	30 db absolute loss	1.47
Steel reinforced aircraft tire 17.00-20 22 PR (18 plys nylon)	a) 68 db absolute loss b) 3.9 db/PLY layer	---

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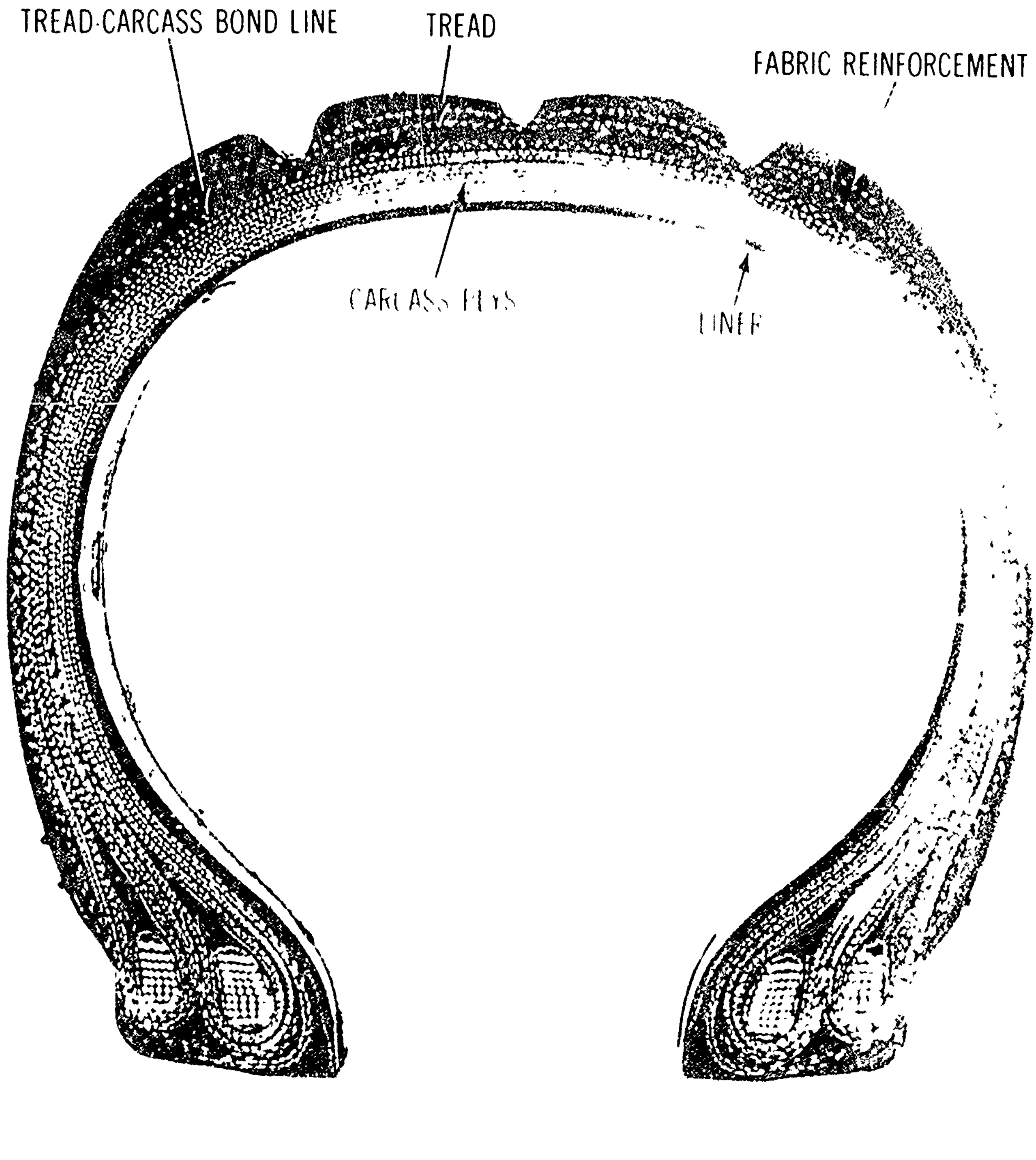
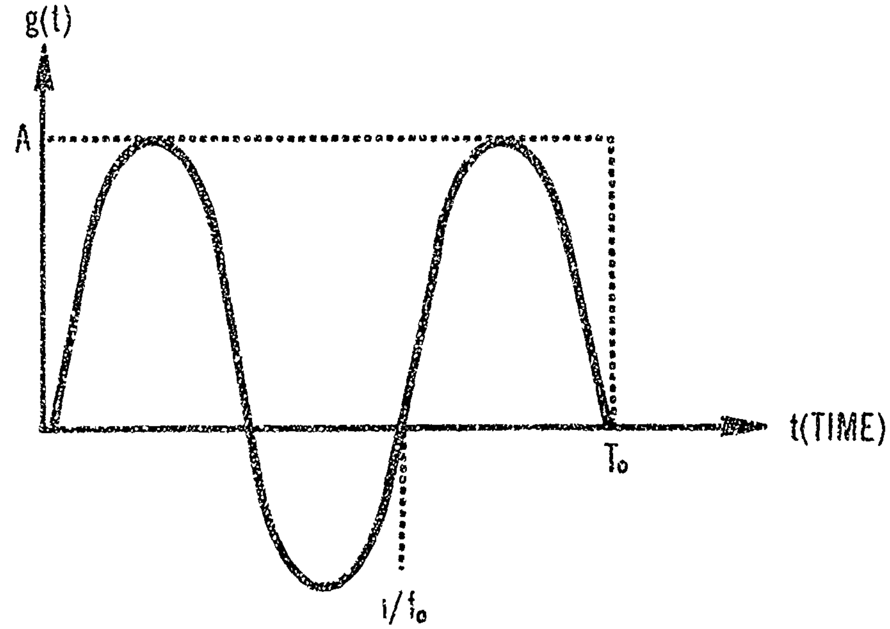
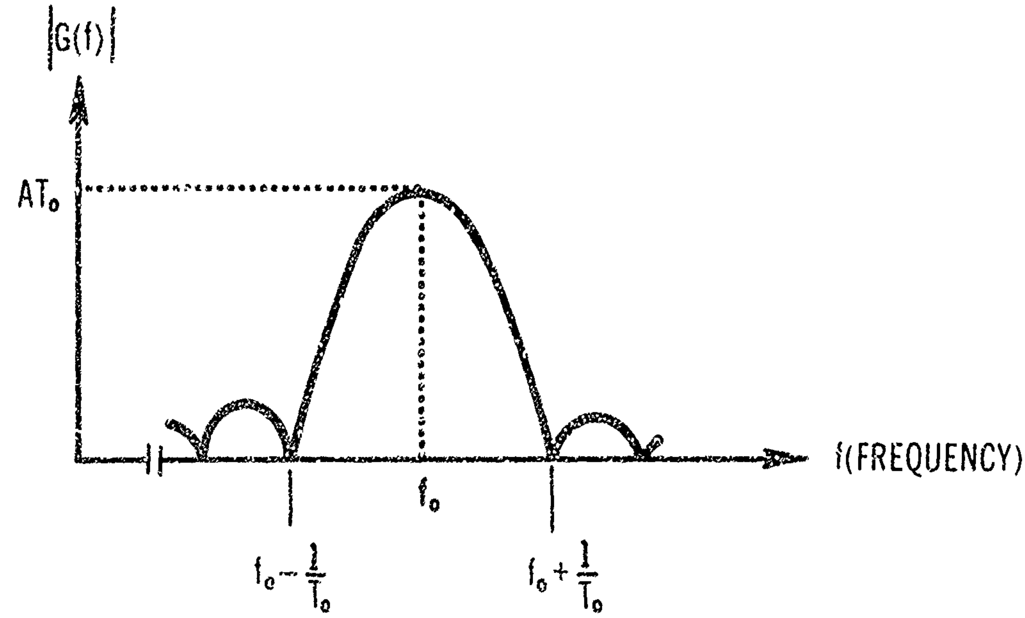


FIGURE 1 SECTIONAL VIEW OF AN AIRCRAFT TIRE



TIME PULSE SIGNAL



FREQUENCY DOMAIN REPRESENTATION OF INDICATED PULSE, WHERE

$$G(f) = \int_{-\infty}^{\infty} g(t) e^{-2\pi i f t}\, dt$$

FIGURE 2 FREQUENCY SPECTRUM OF A SHORT DURATION SINUSOIDAL ULTRASONIC PULSE. $g(t) = A[U(t) - U(t-T_o)] \, \mathrm{Sin}(2\pi f_o t)$. WHERE U IS THE UNIT STEP FUNCTION

0.05 VOLTS/DIV

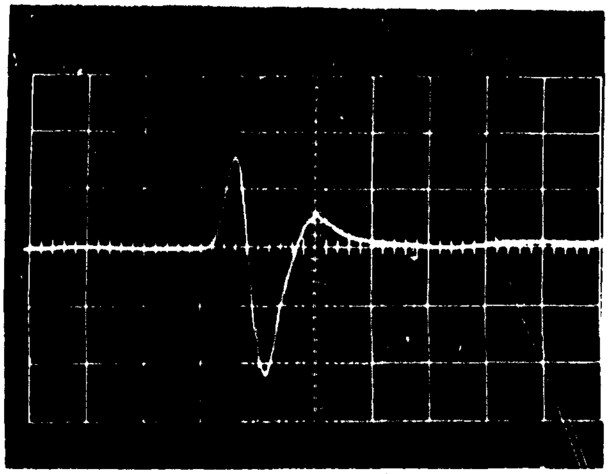


Fig. 3a
D = 10.4 cm

2μ sec/div

0.05 VOLTS/DIV

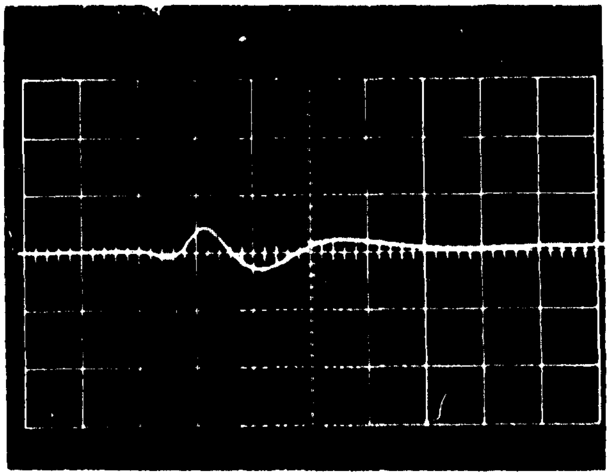


Fig. 3b
D = 20.8 cm

2μ sec/div

0.01 VOLTS/DIV

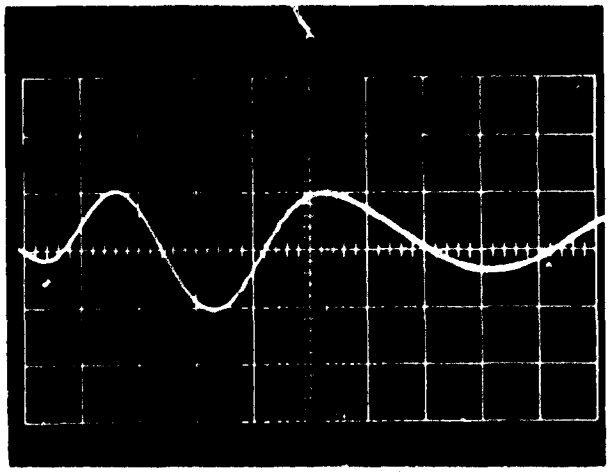
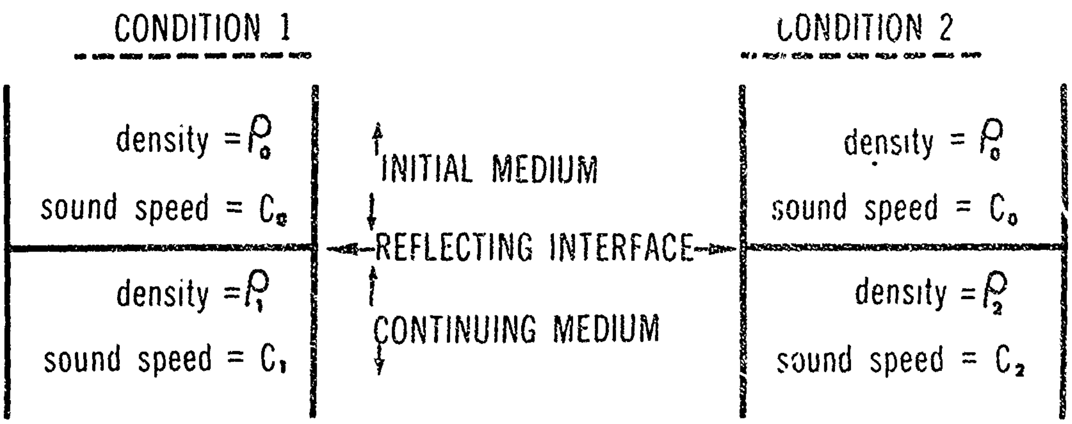


Fig. 3c
D = 41.6 cm

2μ sec/div

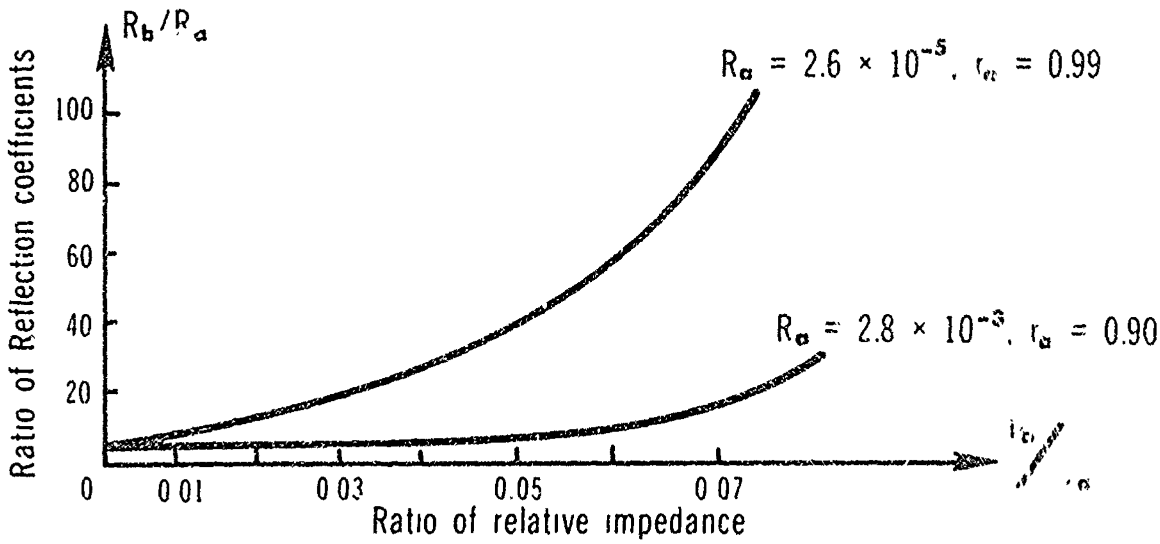
FIGURE 3 ACOUSTIC PULSE DISPERSION IN RUBBER
(RECEIVED SIGNAL AFTER PROPAGATING DISTANCE 'D'
THROUGH NATURAL FILLED VULCANIZED RUBBER)

Fig. 4a INTERFACE CONDITIONS. CHANGE IS FROM CONDITION 1 TO CONDITION 2



THE INTERFACE IS CHARACTERIZED BY THE RATIOS, $r_a = z_1 / z_0$ AND $r_b = z_2 / z_0$, OF THE ACOUSTIC IMPEDANCES $z_0 = \rho_0 c_0$, $z_1 = \rho_1 c_1$ AND $z_2 = \rho_2 c_2$

Fig. 4b RELATIVE CHANGE IN REFLECTION COEFFICIENT, Rb/Ra, RESULTING FROM THE CHANGE IN INTERFACE PROPERTIES FROM CONDITION 1 TO 2.



THE REFLECTION COEFFICIENTS R_a AND R_b ARE GIVEN BY $R^2_a = (1-r_a)/(1+r_a)$. $R^2_b = (1-r_b)/(1+r_b)$.

FIGURE 4 - CHANGE IN REFLECTION COEFFICIENT WITH SMALL CHANGES IN REFLECTING INTERFACE PROPERTIES FOR PLANE WAVES.

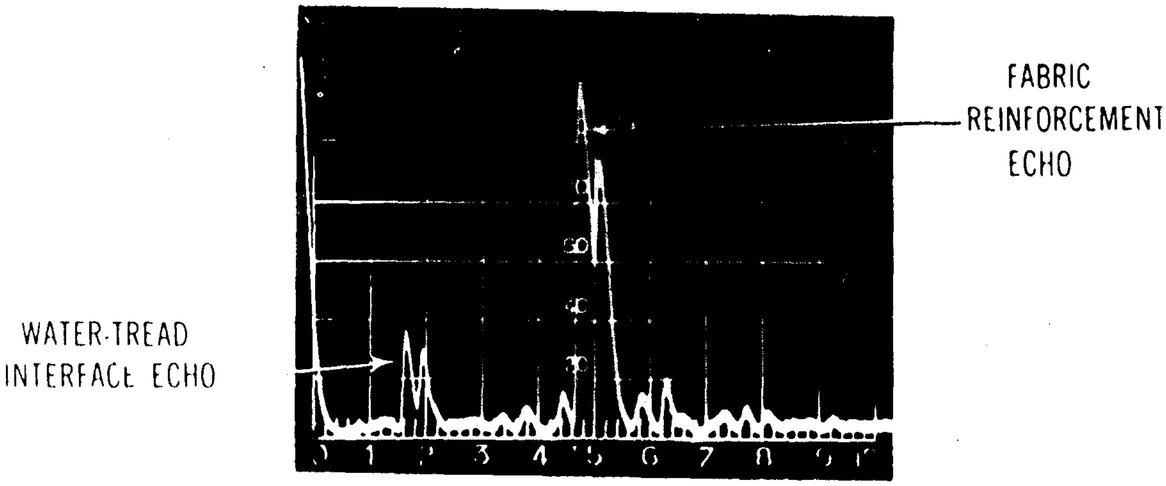


Fig. 5a NORMAL FILTERED PRESENTATION OF FABRIC REINFORCEMENT ECHO AMPLITUDE

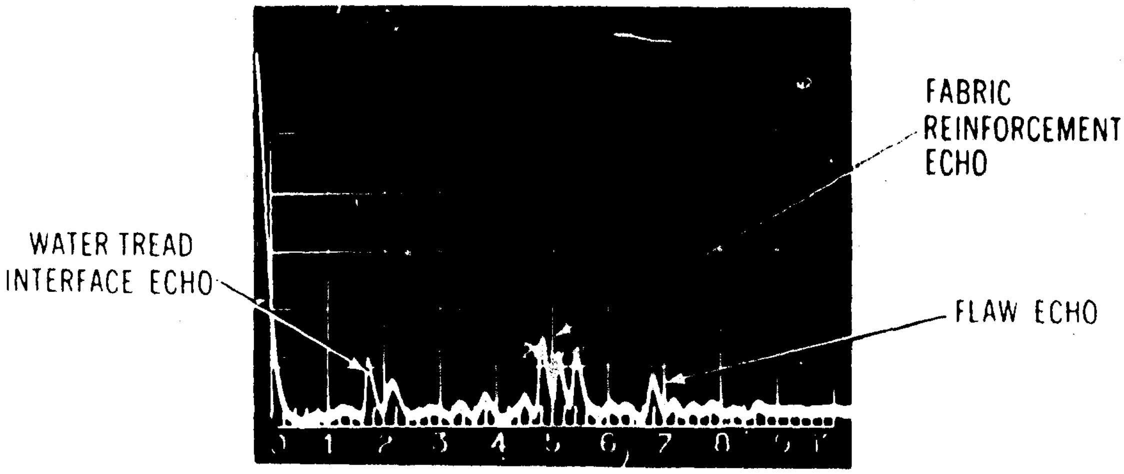


Fig. 5b FABRIC REINFORCEMENT ECHO AMPLITUDE DECREASE ABOVE A 1 in DIAMETER SEPARATION.
Instrument settings are identical to those of 5a

FIGURE 5 NADC ECHO AMPLITUDE MONITORING INSPECTION TECHNIQUE

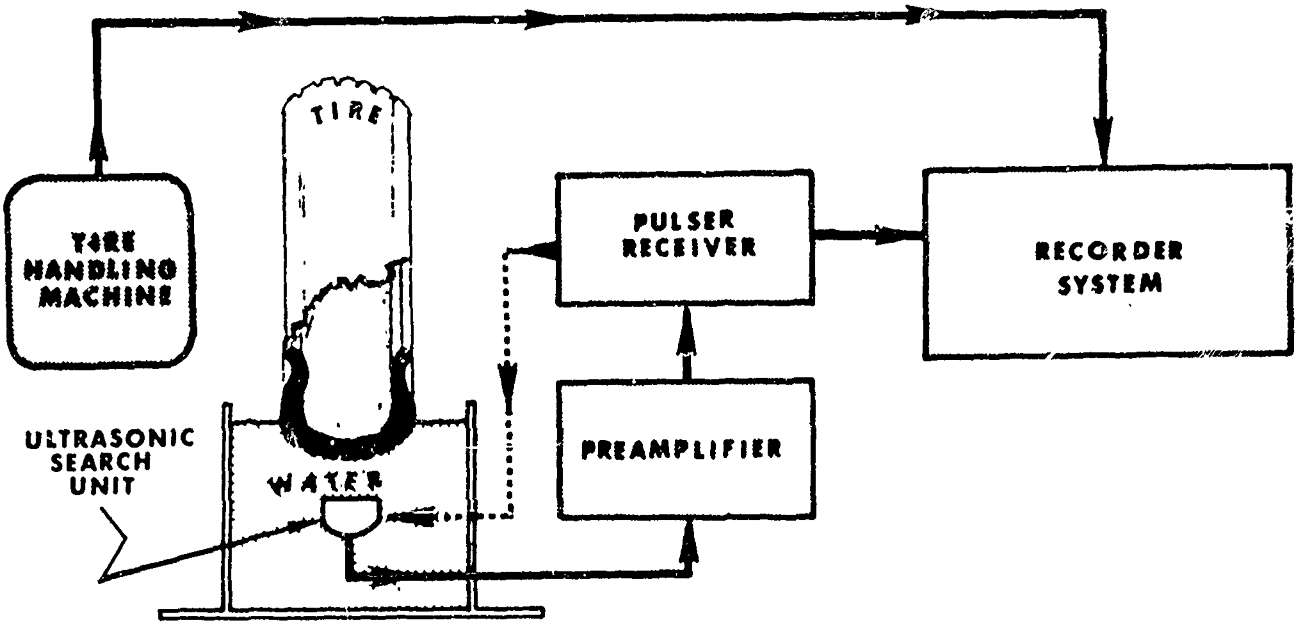


Fig. 6a

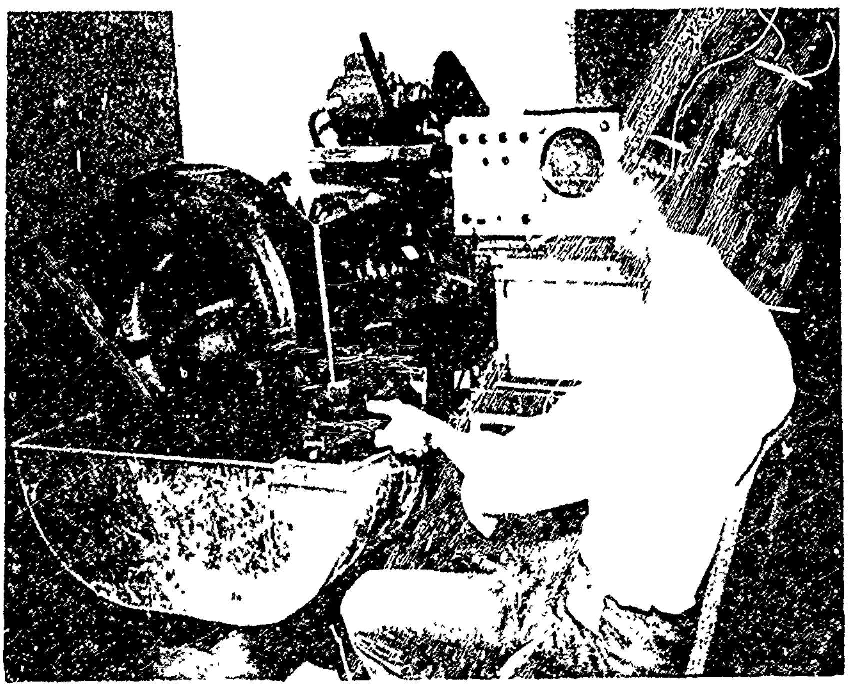


Fig. 6b

FIGURE 6 - ULTRASONIC PULSE-ECHO TIRE INSPECTION SYSTEM

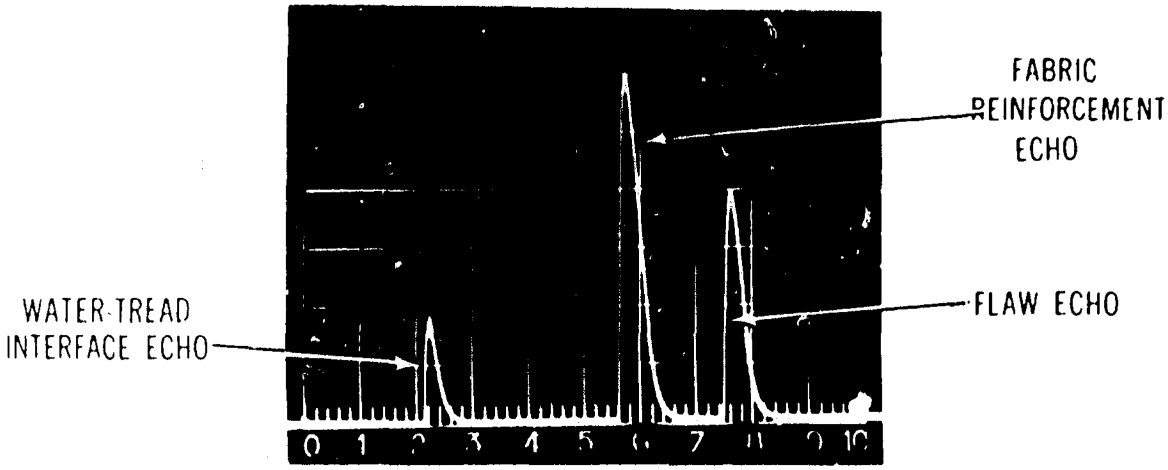


Fig 7a TRACE PRODUCED WITH SUPPRESSION AND SWEPT GAIN

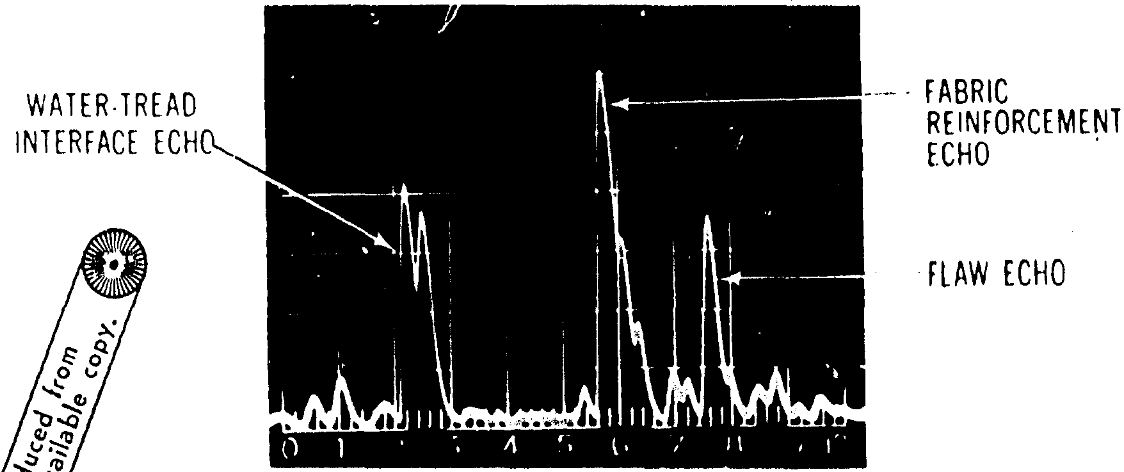


Fig 7b NORMAL FILTERED PRESENTATION

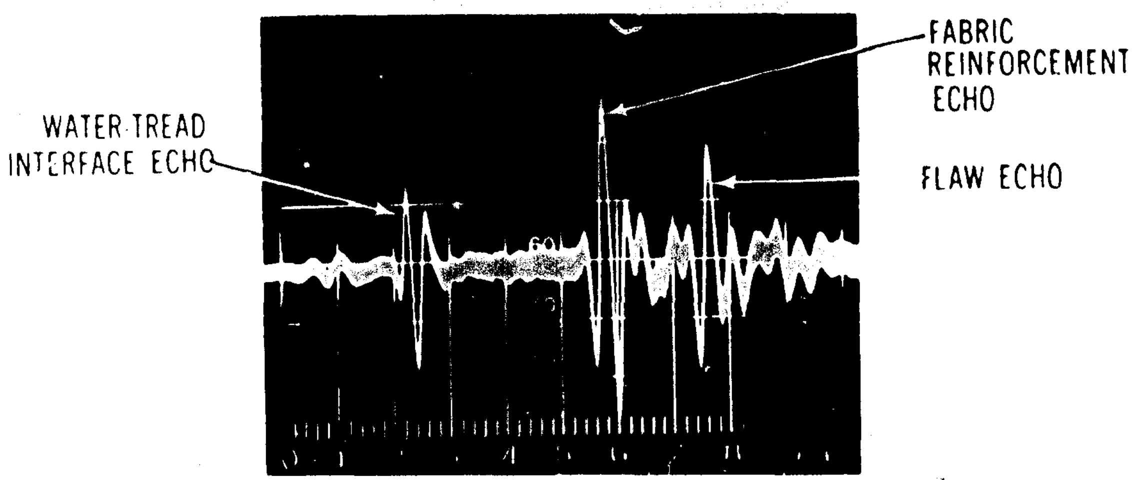


Fig 7c R F PRESENTATION (ACTUAL RECEIVED SIGNALS)

FIGURE 7 TIRE ECHO PHOTOGRAPHS (INCLUDING 1 in DIAMETER SEPARATION ECHO

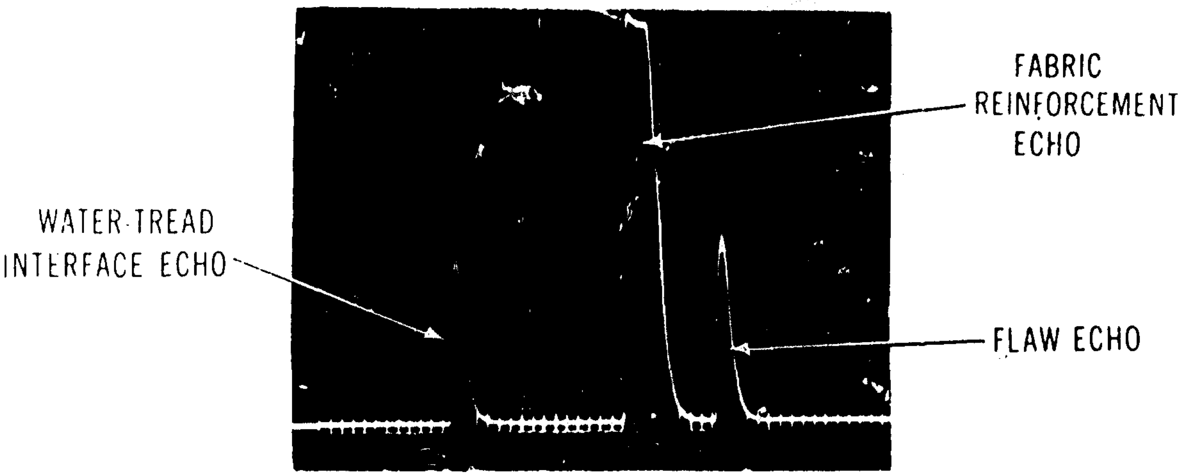


Fig. 8a - TRACE PRODUCED WITH SUPPRESSION AND SWEPT GAIN

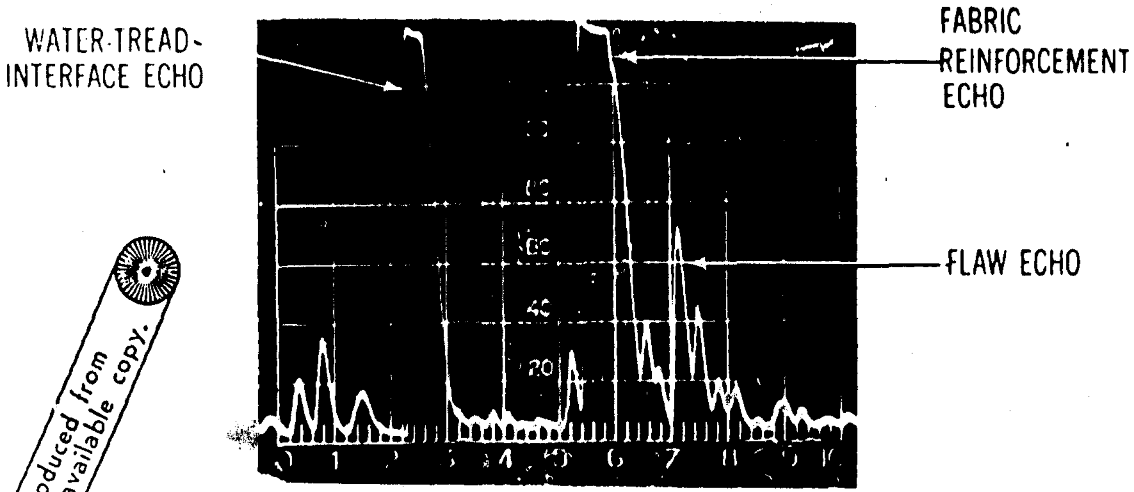


Fig 8b NORMAL FILTERED PRESENTATION

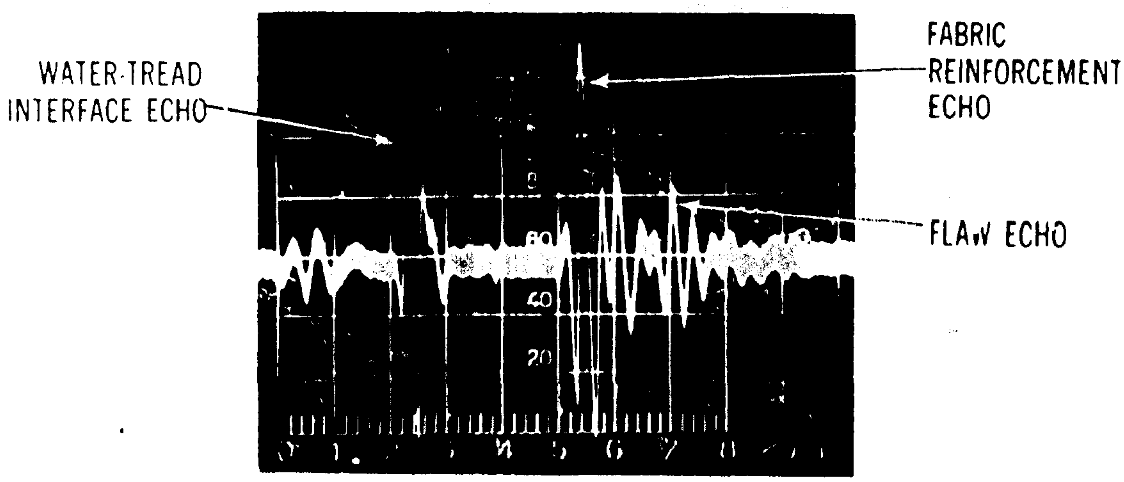


Fig. 8c RF PRESENTATION (ACTUAL RECEIVED SIGNALS)

FIGURE 8 TIRE ECHO PHOTOGRAPHS INCLUDING ½in DIAMETER SEPARATION ECHO